Development of an Infrared Imaging Bolometer

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Introduction

As magnetic fusion plasmas become larger, hotter, and therefore contain more energy, precise control of the plasma becomes even more critical. Today's fusion plasmas are generally "shaped" to allow for more efficient confinement of the plasma by magnetic fields. Shaping requires the plasma position to be both measured and controlled on timescales ranging from milliseconds to hours. This control requires a range of diagnostic tools that measure as many plasma parameters as possible. These plasma diagnostics must be able to survive for long periods in a harsh environment consisting of nuclear radiation (gamma rays and neutrons), vacuum conditions, exposure to plasma bombardment, and strong magnetic fields. In developing such diagnostics, the necessary access requirements, sensitivity, noise, and cost per channel (of a multichannel instrument) must also be considered. To meet these needs, we have developed and patented an imaging bolometer system (U.S. Patent 5,861,625) using infrared readout of a segmented metal foil. Our bolometer allows hundreds to thousands of channels of data, it requires no wiring harness, and it is intrinsically radiation-hard.

Infrared Imaging Bolometer

A bolometer is an instrument that measures the total radiation incident upon it, preferably with an appropriate time resolution. Bolometers are used to study the radiation emission profiles of fusion plasmas, which provide valuable information about the locations and amounts of plasma impurities. Often, the radiation emitted by a fusion-grade plasma is "hollow," that is, it is localized in the outer regions of the plasma. The magnitude of the radiation emitted by the plasma will usually be in the range of 10–100% of the heating power (from 10 kW up to tens of Megawatts), which sustains the plasma. Most bolometers use a material, such as gold, platinum, or tantalum, to absorb the radiation and convert it into heat. The resulting temperature increase is detected by monitoring some physical characteristic of the material. This characteristic could be the change in resistance, a piezo-electric effect, or (in our case) the amount of infrared radiation emitted by the absorbing material. In all present-day, large-scale plasma devices, large arrays of single-element bolometers have been used to measure the plasma's radiation profile. The systems are hampered by the fact that each detector requires at least two wires carrying low-level signals through the vacuum vessel to the outside world. The wiring is difficult to install and maintain (insulators degrade in radiation fields), and it is a source of background noise.

Bolometers are not a new diagnostic. Our work, however, offers new capabilities for plasma diagnostics by combining the latest digital state-of-the-art infrared video technologies (developed originally for missile interceptor programs and the Clementine spacecraft that flew to the moon). These infrared video cameras operate in the 3- to 12-µm wavelength band with

12-bit dynamic range, sensitivity limits of $\Delta T = 0.01°C$, arrays of 256×256 elements, and read-out rates of up to 1 kHz, and are now commercially available. We use such a camera to view a customized segmented-foil that we developed, generating a time-resolved image of the radiation emitted from a plasma.

Radiation damage on conventional bolometers, which need insulators for wiring and usually have multilayered thin film materials that might blister under intense radiation exposure, is a serious concern for the next generation of fusion experiments and reactors. Our bolometer offers an elegantly simple solution. It uses no wires and no insulators, it uses only metal components near the plasma, and it relies on the bulk property (thermal heat capacity) of a metal. These characteristics make this instrument very robust, relatively radiation-resistant, and more stable over the long term. Given these characteristics, it is possible that our instrument might be used on an International Thermonuclear Experimental Reactor (ITER) class (1 GW level) fusion reactor for long periods of time before requiring replacement.

In years past, infrared readout of the back side of a single, thin-foil “detector” has been used to measure the radiation power incident on the front side of the foil. Such detectors were typically used to eliminate particularly difficult electromagnetic interference problems that arise due to pick-up in the leads of traditional resistive readout bolometers. Similarly, infrared cameras have been used to take “snapshots” of the distribution of heat on a foil exposed to a pulsed ion or neutral beam. Such snapshots can be used to diagnose the beam profile, but they do not provide any time resolution. The initial heat distribution is “frozen in” on the foil for a few video frames. To measure a subsequent beam pulse, the researcher had to wait until the heat either diffused or radiated away and then “reinitialize” the foil to avoid confusion. This technology has many limitations. For example, to simultaneously use hundreds or thousands of detectors (bolometer “pixels”), the researcher must have a way to keep the heat deposited on one pixel from flowing into the adjacent pixel, or risk confusing the measurements. In addition, if the expected temperature rise on the foil is around 10°C per second, as it would be in long-pulse plasma applications, then the foil material would melt without active cooling.

Our goal was to develop a multi-element imaging bolometer that is actively cooled, but with thermally isolated pixels. Our first idea was to use a “back-cooled, front-viewed” configuration. The concept was tested with a bed of roofing nails, as shown in Fig. 1. Each nail (pixel) is thermally isolated from its neighbor and cooled by an “infinite heat sink” in which the nail is anchored. In this design, the decay time of the heat on the nails was much too long for plasma applications, but it provides a good graphical illustration of the concept of a segmented sensor matrix.

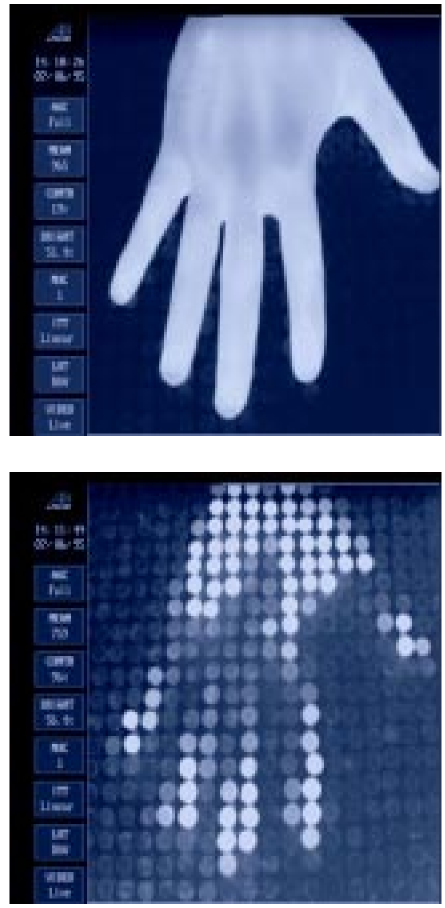
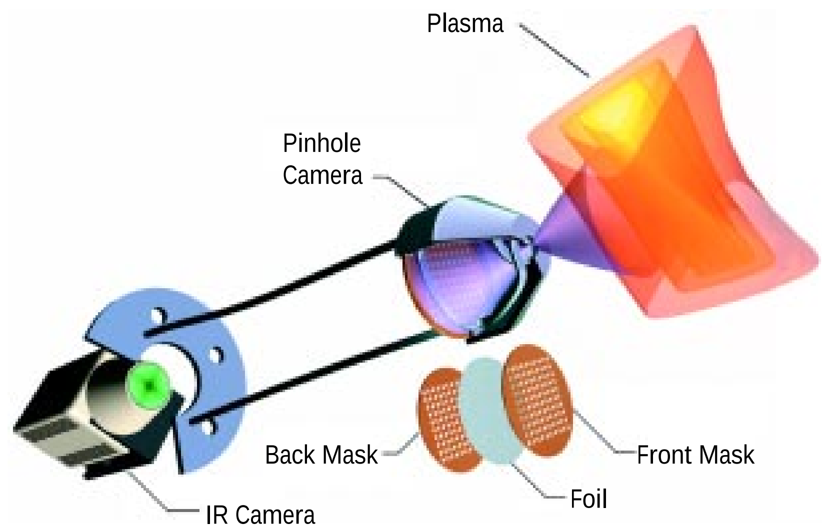


***Fig. 1** An array of 20 × 20 roofing nails was used to test the concept of a “back-cooled, front-viewed” bolometer configuration. The heads of the nails are thermally isolated from each other, as shown in these two infrared pictures. The top image is a hand, and the bottom image is the thermal image of the hand remaining on the heads of the nails.*

Subsequently, we changed to a “back-viewed, side-cooled” design, recognizing that stray thermal radiation from hot armor tiles in the plasma vacuum vessel might contaminate the measurement. This modified design is shown in an artist’s conception in Fig. 2. To maximize the sensitivity (minimize the heat capacity), the foil must be as thin as is mechanically possible; however, to ensure that the desired range of plasma radiation (up to ~1–10 keV photons) is absorbed in the foil, the foil must be thick enough to stop soft x-ray photons.

***Fig. 2** Artist’s sketch of the infrared imaging bolometer, which employs a pinhole camera design with a mask/foil combination viewed by a digital infrared video camera.*



International Collaboration

In the absence of a Los Alamos-based, large-scale fusion plasma research facility, Los Alamos scientists pursue international collaborations to field new diagnostic tools. In the Plasma Physics Group (P-24), we are involved in ongoing collaborations with researchers at the Japanese Atomic Energy Research Institute (JAERI) using the JT-60U machine, which is the world’s largest operating tokamak. We are also collaborating with researchers at the National Institute for Fusion Science (NIFS) in Toki, Japan, where the Large Helical Device (LHD), a $1B-class superconducting stellarator, will soon be in operation (see Fig. 3). As part of the U.S. Department of Energy Japan Fusion Exchange Agreement, we began collaborating with NIFS scientists to develop a plasma diagnostic that would meet the needs of the future LHD.

The LHD plasma will have a complex, helical shape. To understand the behavior of this plasma, multiple sight-lines and preferably even multiple imaging diagnostics will be required. In addition, because the LHD is a superconducting machine, long pulse operations will be used. These pulse operations might range from 10 minutes to one hour, limited only by heating in the sources and the available electric power grid. Such long-pulse operation will require a diagnostic that is able to gather enormous quantities of data with real-time data-handling capabilities.

In the summer of 1997, we performed the first plasma tests on a prototype diagnostic system using the Compact Helical Stellarator (CHS) plasma at Nagoya University. Using an Amber Radiance 1 digital infrared camera (3- to 5-μm band) with 25-millidegree sensitivity and both 0.5- and 1.0-μm thick gold foils, we obtained signals from a short-pulse (~100-ms duration) plasma heated by electron cyclotron and neutral beam sources. We blackened the backside of the gold foils with a carbon spray to obtain a thermal emissivity of nearly 1, which means that each foil's infrared emission represents its temperature. In addition to the expected signals, we found unwanted heating from stray microwave radiation used to create and heat the plasma. Typically, 10 mW of energy produces a signal of 4°C on the foil.

We performed a second series of tests in spring of 1998 using an Agema Thermovision camera (8- to 12-μm band) with a fast linescan (2.5 kHz) mode of operation, which allowed better time resolution, more in accordance with the short duration

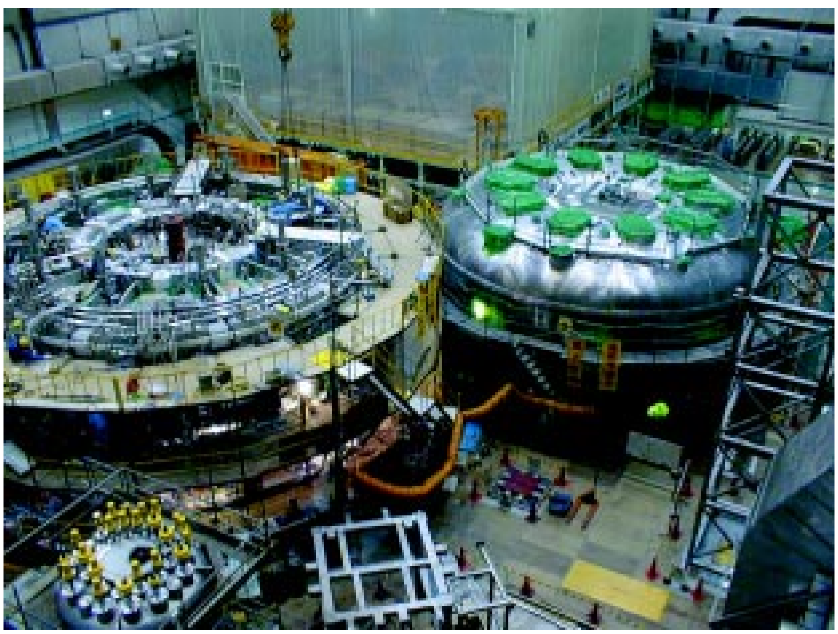


***Fig. 3** The superconducting LHD device under construction in October 1997 at the NIFS site in Toki, Japan. The stainless steel cyrostat is visible on the right, while the stellarator is largely hidden by scaffolding on the left.*

(~100 ms) test plasma. These tests fully qualified the instrument and our models, and will allow us to proceed with the real diagnostic on the LHD plasma.

Upcoming Work

In the coming year, we hope to install a second-generation prototype of our imaging bolometer on a shared port with a tangential view in the superconducting, long-pulse LHD. This will give us a view of the full plasma cross section, and it should allow us to obtain time-resolved images of the total plasma radiation similar to the visible light image in Fig. 4 (but with less spatial resolution). Based on the tests to date, our imaging bolometer already shows great promise in becoming a key diagnostic for the LHD, the world's largest superconducting experimental fusion device. We anticipate that the success of this collaboration will lead us to apply our diagnostic and pulsed-power skills to other major fusion experiments around the country and the world.

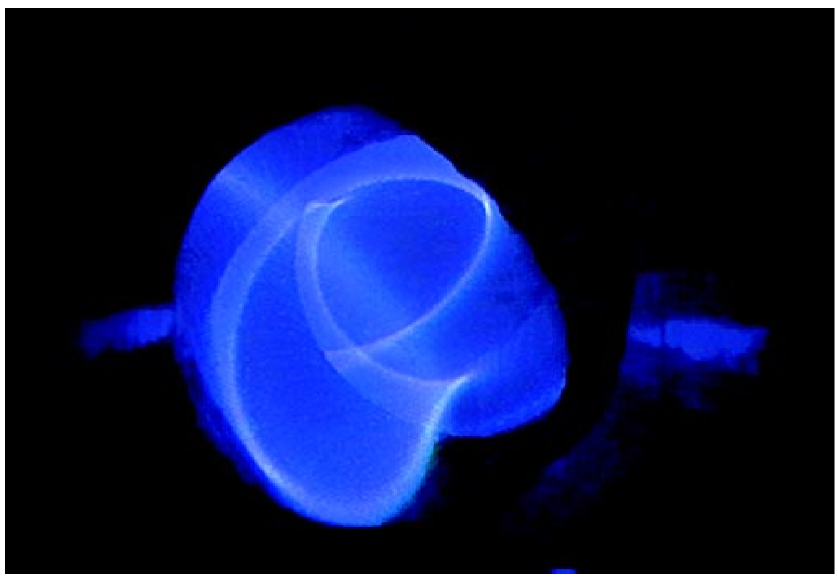


***Fig. 4** The complex shape of today's plasmas, as seen in this visible light tangential view of the LHD stellarator in Toki, Japan, requires diagnostics with imaging capabilities.*

Further Reading

G. A. Wurden, “ A Rad-Hard, Steady-State, Digital Imaging Bolometer System for ITER,” in *Diagnostics for Experimental Thermonuclear Fusion Reactors*, P. E. Stott, *et. al.*, Eds. (Plenum Press, New York, 1996), pp. 603–606.

G. A. Wurden and B. J. Peterson, “Imaging Bolometer Development for Large Fusion Devices,” ITER Diagnostics Workshop (Varenna, Italy, September 1997), in *Diagnostics for Experimental Thermonuclear Fusion Reactors*, P. E. Stott, *et. al.*, Eds. (Plenum Press, New York, 1998), pp. 399–408.

G. A. Wurden, B. J. Peterson, and S. Sudo, “Design of an Imaging Bolometer System for the Large Helical Device,” *Review of Scientific Instruments* 68, 766 (1997).